Constraining the growth factor with baryon oscillations

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The growth factor of linear fluctuations is probably one of the least known quantity in observational cosmology. Here we discuss the contraints that baryon oscillations in galaxy power spectra from future surveys can put on a conveniently parametrized growth factor. We find that spectroscopic surveys of 5000 deg^2 extending to $z \approx 3$ could estimate the growth index γ within 0.06; a similar photometric survey would give $\Delta\gamma \approx 0.15$. This test provides an important consistency check for the standard cosmological model and could constrain modified gravity models. We discuss the errors and the figure of merit for various combinations of redshift errors and survey sizes.

I. INTRODUCTION

The characterization of dark energy (DE) has been so far based almost uniquely on background tests at rather low redshifts ($z \leq 1.5$: Riess et al. 1998, Perlmutter et al. 1999, Tonry et al. 2003, Riess et al. 2004, Astier et al. 2006, Eisenstein et al. 2005) or very large redshifts ($z \approx 1000$: e.g. Netterfield et al. 2002, Halverson et al. 2002, Lee et al. 2002, Bennett et al. 2003, Spergel et al. 2006). These tests are based essentially on estimations of luminosity $D_L(z)$ or angular-diameter distances $D(z)$, i.e. on integrals of the Hubble function $H(z)$ which, in turn, contain integrals of the equation of state. Only very recently tests involving the linear perturbations have begun to be discussed, using methods based on the integrated Sachs-Wolfe effect, weak lensing and high-redshift power spectra (e.g. Boughn & Crittenden 2004, Refregier et al. 2006, Crotts et al. 2005). However, it is fair to say that the growth function is still one of the least known quantity in cosmology. So far, it is possible to quote only two published results that put limits on it: the value at $z \approx 0.15$ obtained in 2dF (Hawkins et al. 2003; Verde et al. 2002) and the $z \approx 3$ result from Lyman$-\alpha$ clouds (McDonald et al. 2005). Defining $G(z) = \delta(z)/\delta(0)$ (δ being the matter density contrast) we have for

$$f \equiv \frac{d \log G}{d \log a} \tag{1}$$

the value $f = 0.51 \pm 0.15$ for 2dF at $z \approx 0.15$ and $f = 1.46 \pm 0.29$ for the Lyman-α at $z \approx 3$. These results show clearly how large is the degree of uncertainty. Actually the uncertainty is much larger than it appears from the quoted statistical errors. In the case of the low-z estimate, the result is obtained by estimating the bias from higher-order statistics, which is known to be particularly sensitive to the selection effects, to incompleteness etc.; different methods give in fact quite different results (see discussion in Hawkins et al. 2003). In the case of the high-z estimation, the main problem is the reconstruction of the bias factor from numerical simulations which, by their nature, are performed only in a limited range of fiducial models. It is therefore important to test the growth factor with other methods and with improved datasets.

A test of the growth factor would be important both as a consistency check for the standard cosmological model (since f is determined by $H(z)$ in a standard cosmology) and as a constraint on non-standard models like e.g. modified gravity. In fact, models that modify the Poisson equation will also generically modify the perturbation equation for the matter density contrast δ. As an example, models in which dark energy is coupled to matter display a growth index which deviates from the standard case at all epochs (see e.g. Amendola & Tocchini-Valentini 2003; Demianski et al. 2004; Nunes & Mota 2004). Several other papers discussed the parametrization of the perturbation equations in modified gravity models, see e g. Ishak et al. (2005), Heavens, Kitching and Taylor (2006), Taylor et al. (2007); Heavens, Kitching, Verde (2007) , Caldwell, Cooray and Melchiorri (2007), Amendola, Kunz and Sapone (2007), Zhang et al. (2007).

In this paper we investigate the extent to which baryon oscillations can set limits to $G(z)$ in future large-scale observations at z up to 3. The method we use is based on recent proposals (Linder 2003, Blake & Glazebrook 2003, Seo & Eisenstein 2003) to exploit the baryon acoustic oscillations (BAOs) in the power spectrum as a standard ruler calibrated through CMB acoustic peaks. In particular, Seo & Eisenstein (2003; SE) have shown the feasibility of large (100 to 1000 square degrees) spectroscopic surveys at $z \approx 1$ and $z \approx 3$ to put stringent limits to the equation of state $w(z)$ and its derivative. As it is well-known, BAOs have been detected at low z in SDSS (Eisenstein et al. 2005); the detection at large z , where more peaks at smaller scales can be obtained, is likely to become one of the most interesting astrophysical endeavours of the next years.

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II. BACKGROUND EQUATION

Here we review the basic equations and notation for the background evolution and for the linear fluctuations. The evolution of the dark energy can be expressed by the present dark energy density Ω_{DE} and by a time-varying equation of state (see Copeland, Sami & Tsujikawa 2006 for a recent review):

$$w(z) = \frac{p}{\rho} \tag{2}$$

Given $w(z)$, the dark energy density equation is $\rho(z) = \rho(0)a^{-3(1+\hat{w})}$ where

$$\hat{w}(z) = \frac{1}{\log(1+z)}\int_0^z \frac{w(z')}{1+z'}dz' \tag{3}$$

The Hubble parameter and the angular diameter distance, $H(z)$ and $D_A(z)$, assuming a flat universe $\Omega_m + \Omega_{DE} = 1$, become respectively:

$$H^2(z) = H_0^2[\Omega_{m_0}(1+z)^3 + (1-\Omega_{m_0})(1+z)^{3(1+\hat{w})}] \tag{4}$$

and

$$D_A(z) = \frac{c}{1+z}\int_0^z \frac{dz'}{H(z')} \tag{5}$$

where the total matter density is

$$\Omega_m(z) = \frac{\Omega_{m_0}}{\Omega_{m_0} + (1-\Omega_{m_0})(1+z)^{3\hat{w}}} \tag{6}$$

It is well known that a good approximation to the growth index for sub-horizon scales in flat models is given by (Lahav et al. 1991, Wang and Steinhardt 1998)

$$f \equiv \frac{\partial \log G}{\partial \log a} = \Omega_m(a)^{\gamma} \tag{7}$$

This introduces a new parameter γ, beside those that characterize the background model (see also Linder 2005, Percival 2005) .

We remark that a recent analysis of most of the extant data produced the result $\gamma = 0.6^{+0.4}_{-0.3}$ (Di Porto & Amendola 2007) .

III. FISHER MATRIX FORMALISM

Following Seo & Eisenstein (2003; hereinafter SE) we write schematically the observed galaxy power spectrum as:

$$\begin{aligned} P_{obs}(z,k_r) &= \frac{D_{Ar}^2(z)H(z)}{D_A^2(z)H_r(z)}G^2(z)b(z)^2\left(1+\beta\mu^2\right)^2 P_{0r}(k) \\ &+ P_{shot}(z) \end{aligned} \tag{8}$$

where the subscript r refers to the values assumed for the reference cosmological model, i.e. the model at which we evaluate the Fisher matrix. Here P_{shot} is the shot noise due to discreteness in the survey, μ is the direction cosine within the survey, P_0 is the present spectrum for the fiducial cosmology. For the linear matter power spectrum we adopt the fit by Eisenstein & Hu (1999) (with no massive neutrinos and also neglecting any change of the shape of the spectrum from small deviation around $w = -1$).

The wavenumber k is also to be transformed between the fiducial cosmology and the general one (SE; see also Amendola, Quercellini, Giallongo 2004, hereinafter AQG, for more details). The bias factor is defined as:

$$b(z) = \frac{\Omega_m(z)^{\gamma}}{\beta(z)} \tag{9}$$

and for the fiducial model is estimated by comparing the 8Mpc/h cell variance $\sigma_{8,g}$ of the galaxies corrected for the linear redshift distortion with the same quantity for the total matter. Clearly, the growth function is degenerate with the bias except for the redshift correction factor $(1+\beta\mu^2)$. Since we marginalize over β, it is clear that the redshift correction plays a crucial role for as concern the estimation of the growth factor. The linear correction we use should therefore be considered only a first approximation and more work to go beyond Kaiser's small-angle and Gaussian approximation is needed, as discussed in Hamilton & Culhane (1996), Zaroubi & Hoffman (1996), Tegmark et al. (2004) and Scoccimarro (2004).

The total galaxy power spectrum including the errors on redshift can be written as (SE)

$$P(z,k) = P_{obs}(z,k)\, e^{k^2\mu^2\sigma_r^2} \tag{10}$$

where $\sigma_r = \frac{\delta z}{H(z)}$ is the absolute error on the measurement of the distance and δz is the absolute error on redshift. Given the uncertainties of our observations, we now want to propagate these errors to compute the constraints on cosmological parameters. The Fisher matrix provides a useful method for doing this. Assuming the likelihood function to be Gaussian, the Fisher matrix is (Eisenstein, Hu & Tegmark 1998; Tegmark 1997)

$$F_{ij} = 2\pi\int_{k_{min}}^{k_{max}} \frac{\partial \log P(k_n)}{\partial\theta_i}\frac{\partial \log P(k_n)}{\partial\theta_j}\cdot V_{eff}\cdot\frac{k^2}{8\pi^3}\cdot dk \tag{11}$$

where the derivatives are evaluated at the parameter values of the fiducial model and V_{eff} is the effective volume of the survey, given by:

$$\begin{aligned} V_{eff} &= \int\left[\frac{n(\vec{r})\,P(k,\mu)}{n(\vec{r})\,P(k,\mu)+1}\right]^2 d\vec{r} = \\ &= \left[\frac{n(\vec{r})\,P(k,\mu)}{n(\vec{r})\,P(k,\mu)+1}\right]^2 V_{survey} \end{aligned} \tag{12}$$

where the last equality holds only if the comoving number density is constant in position and where $\mu = \vec{k}\cdot\hat{r}/k$, $\hat{r}$ being the unit vector along the line of sight and k the wave

	Parameters	
1	total matter density	$\omega_m = \Omega_{m_0} h^2$
2	total baryon density	$\omega_b = \Omega_{b_0} h^2$
3	optical thickness	τ
4	spectral index	n_s
5	present matter density	Ω_{m_0}
	For each redshift bin	
6	shot noise	P_s
7	angular diameter distance	$\log D_A$
8	Hubble parameter	$\log H$
9	growth factor	$\log D$
10	bias	$\log \beta$

Table I: Cosmological parameters

	Parameters	
1	total matter density	$\omega_m = \Omega_{m_0} h^2$
2	total baryon density	$\omega_b = \Omega_b h^2$
3	optical thickeness	τ
4	spectral index	n_s
5	matter density today	Ω_{m_0}
6	tensor scalar ratio	T/S
7	angular diameter distance	$\log D_A$
8	normalization factor	$\log A_s$

Table II: CMB parameters

vector. The highest frequency $k_{max}(z)$ is chosen to be near the scale of non-linearity at z: we choose values from $0.11h$/Mpc for small z bins to $0.33h$/Mpc for the highest redshift bins. Any submatrix of F_{ij}^{-1} gives the correlation matrix for the parameters corresponding to rows and columns on that submatrix. The eigenvectors and eigenvalues of this correlation matrix give the orientation and the size of the semiaxes of the confidence region ellipsoid. This automatically marginalizes over the remaining parameters. The parameters that we use for evaluating the Fisher matrix are shown in Tab. (I). Our fiducial model corresponds to the ΛCDM WMAP3y best-fit parameters (Spergel et al. 2006): $\Omega_{m0} = 0.28$, $h = 0.73$, $\Omega_{DE} = 0.72$, $\Omega_K = 0$, $\Omega_b h^2 = 0.0223$, $\tau = 0.092$, $n_s = 0.96$ and $T/S = 0$ and as anticipated $\gamma = 0.545$. Beside the BAO from large scale structure, we also employ the CMB Fisher matrix, following the method in Eisenstein, Hu & Tegmark (1999) and assuming a Planck-like experiment. The cosmological parameters we use for CMB are listed in Tab. (II). The total Fisher matrix is given simply by the addition of the two matrices.

The derivatives of the spectrum with respect to the cosmological parameters p_i (i.e. $\omega_m = \Omega_{m_0} h^2$, $\omega_b = \Omega_{b_0} h^2$, τ, n_s , Ω_{m_0} plus P_s, β, G, D, H for each redshift bin) are evaluated using the fit of Eisenstein & Hu (1999).

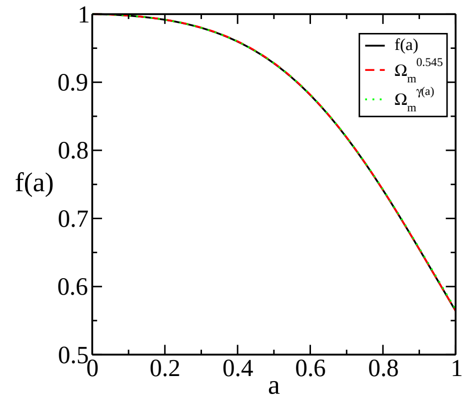

Figure 1: Growth index vs the scale factor for a DE model with a varying equation of state, $w(z) = w_0 + w_1 z$ with $w_0 = -1.5$ and $w_1 = 1$. The black solid line refers to the solution obtained by the differential equation for γ (Percival 2005). The red dashed line refers to the growth index given by eq. (7) and the green dotted line is the growth index with a γ factor given by eq. (17). The matter density is given by eq. (6).

Since we want to propagate the errors to the cosmologically relevant set of parameters

$$q_i = \{ w_0, w_1, \gamma \} \tag{13}$$

we need to change parameter space. This will be done taking the inverse of the Fisher Matrix F_{ij}^{-1} and then extracting a submatrix, called F_{mn}^{-1} containing only the rows and columns with the parameters that depend on q_i, namely D_A, H and G. The root mean square of the diagonal elements of the inverse of the submatrix give the errors on D_A, H, and G. Then we contract the inverse of the submatrix with the new set of parameters q_i; the new Fisher matrix will be given by

$$\overline{F}_{DE;ij} = \frac{\partial p_m}{\partial q_i} \overline{F}_{mn} \frac{\partial p_n}{\partial q_j} \tag{14}$$

This automatically marginalizes over all the remaining parameters.

The derivatives of the Hubble parameter and for the angular diameter distance can be written as

$$\frac{\partial \log\ H}{\partial q_i} = \frac{1}{H} \frac{\partial H}{\partial q_i} \tag{15}$$

$$\frac{\partial \log\ D_A}{\partial q_i} = -\frac{1}{(1+z)\, D_A} \int \frac{\partial \log\ H}{\partial q_i} \frac{1}{H} dz \tag{16}$$

IV. GROWTH FACTOR

We consider now separately two cases: in Case 1 the growth rate depends on w (assumed constant); in Case 2 the growth rate is free and we forecast the constraints that future experiments can put on it.

Surveys		
z	V_s (Gpc/h)^3	n
$0-0.5$	0.006	$5 \cdot 10^{-2}$
$0.5-0.7$	0.0082	$6.9 \cdot 10^{-2}$
$0.7-0.9$	0.011	$4.2 \cdot 10^{-2}$
$0.9-1.1$	0.0135	$3.1 \cdot 10^{-2}$
$1.1-1.3$	0.015	$2.4 \cdot 10^{-2}$
$2.7-3.5$	0.073	$2 \cdot 10^{-3}$

Table III: Details of the surveys.

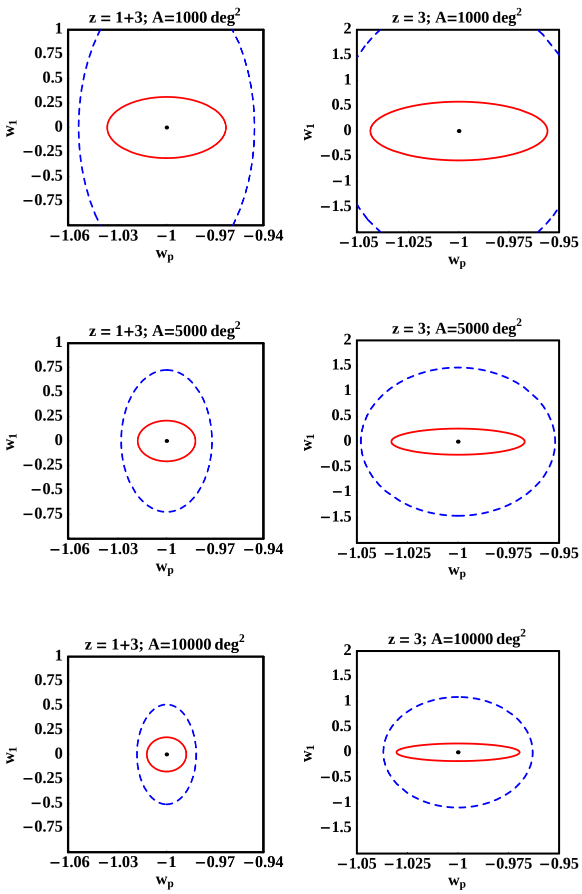

Figure 2: Confidence level for w_p and w_1 for surveys of 1000, 5000 and 10000 deg^2 and for different combinations of redshift bins (case 1). The solid red curve refers to spectroscopic surveys and the dashed blue curve to photometric surveys, $\delta z = 0$ and $\delta z/z = 0.04$ respectively.

A. Case 1

In general, the exponent γ depends on the cosmological parameters. To see this, we just need to consider the equation of perturbations and insert the growth index defined by eq. (1). Then we obtain the approximate analytic solution (Wang & Steinhardt 1998) :

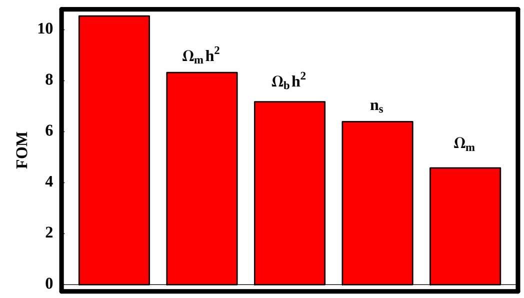

Figure 3: Fom for $w_p - w_1$ vs marginalized parameters.

	1000 deg^2		5000 deg^2		10000 deg^2	
δz	w_p	w_1	w_p	w_1	w_p	w_1
	$z = 1+3$					
0%	0.036	0.313	0.018	0.208	0.012	0.175
4%	0.054	1.523	0.028	0.726	0.018	0.51
	$z = 3$					
0%	0.044	0.579	0.033	0.257	0.030	0.154
4%	0.061	2.614	0.051	1.463	0.034	1.092

Table IV: Values of σ_{w_p} and σ_{w_1} for spectroscopic surveys $\delta z = 0$ and photometric surveys $\delta z = 4\%$ on the redshift estimate and for several survey areas (case 1). We consider two different combinations of redshift ($z = 1+3$ and $z = 3$ only).

$$\gamma(z) = \frac{3}{5 - \frac{w(z)}{1-w(z)}} \tag{17}$$

and for a ΛCDM model $\gamma = 0.545$. The behavior of the growth index for a $w(z)$ model is shown in Fig. (1). We can see that there is almost no difference in behavior between the curves obtained with the approximation (17). Because of the dependence of γ on the dark energy parameters, the derivatives of the growth factor are given by:

$$\frac{\partial \log\ G}{\partial q_i} = -\int \left[\frac{\partial \gamma}{\partial q_i} \log \Omega_m(z) + \gamma \frac{\partial \log \Omega_m(z)}{\partial q_i}\right] \Omega_m(z)^{\gamma} \frac{dz}{(1+z)} \tag{18}$$

In this case the new set of parameters is $q_i = \{\, w_0,\, w_1\}$ and we assume as fiducial model $w_0 = -1, w_1 = 0$. The factor γ, in this case, depends only on the dark energy parameters w_0 and w_1; this means the only non-vanishing derivatives are $\frac{\partial \gamma}{\partial w_0}$ and $\frac{\partial \gamma}{\partial w_1}$. In Fig. (2) the confidence regions are shown for different combination of redshift and area. Instead of (w_0, w_1) we use the pivot parameters $w_p - w_1$ (projection of $w_0 - w_1$ on the pivot point, defined as the value of z for which the uncertainty in $w(z)$ is smallest).

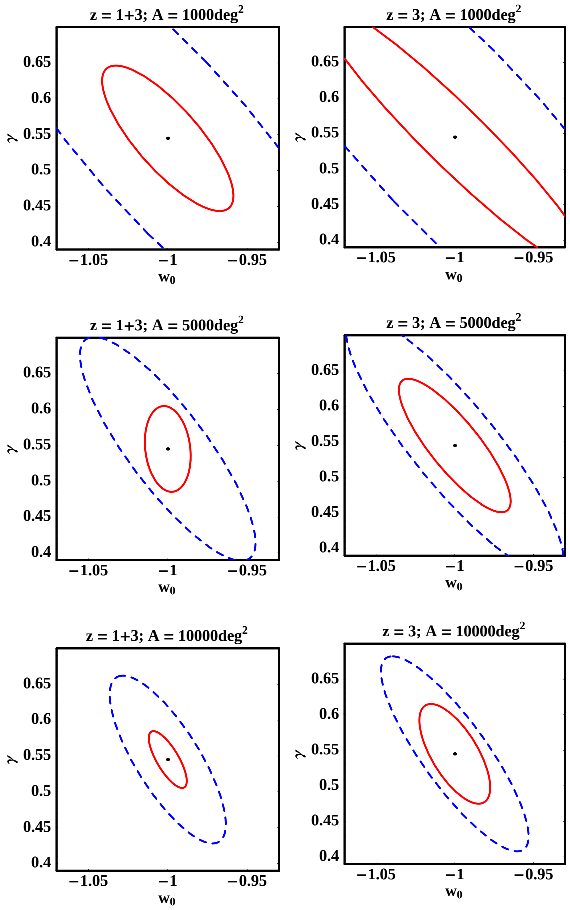

Figure 4: Confidence level for w_0 and γ for surveys of 1000, 5000 and 10000 deg^2 and for different combinations of redshift bins (case 2). The solid red curve refers to spectroscopic surveys and the dashed blue curve to photometric surveys, $\delta z = 0$ and $\delta z/z = 0.04$ respectively.

	1000 deg^2		5000 deg^2		10000 deg^2	
δz	w_0	γ	w_0	γ	w_0	γ
	$z = 1 + 3$					
0%	0.045	0.099	0.016	0.059	0.004	0.05
4%	0.128	0.301	0.062	0.153	0.044	0.114
	$z = 3$					
0%	0.089	0.188	0.039	0.092	0.026	0.069
4%	0.152	0.344	0.076	0.18	0.081	0.197

Table V: Values of σ_{w_0} and σ_γ for spectroscopic surveys $\delta z = 0$ and photometric surveys $\delta z/z = 4\%$ on the measure of the redshift and for several areas (case 2). We consider two different combinations of redshift bins ($z = 1 + 3$ and $z = 3$ only).

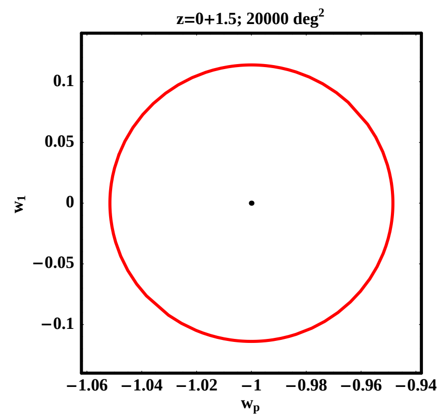

Figure 5: Confidence level for w_p and w_1 for surveys 20000 deg^2 (DETF case). The solid red curve refers to spectroscopic surveys.

B. Case 2

We want now to put constraints on γ as a free parameter. We assume here $w = constant$ and again $w_0 = -1$ as fiducial value. The new set of parameters is therefore $q_i = \{w_0, \gamma\}$. The derivatives with respect to the first three parameters are given by the eq. (18). The derivative for the growth factor with respect to γ is:

$$\begin{aligned} \frac{\partial \log G}{\partial \gamma} &= -\int \frac{\partial}{\partial \gamma} \exp\left[\gamma \log \Omega_m(z)\right] \frac{dz}{(1+z)} = \\ &= -\int \log \Omega_m(z)\, \Omega_m(z)^\gamma \frac{dz}{(1+z)} \end{aligned} \tag{19}$$

V. RESULTS AND CONCLUSIONS

The main aim of this work is to give marginalized constraints on the dark energy parameters $(w_p - w_1)$ and most importantly on the growth factor itself, for several combinations of surveys, redshift errors and area. Following SE and Amendola, Quercellini, Giallongo (2004) we consider several binned surveys with average redshift depth around $z = 1$ and $z = 3$ plus a SDSS-like survey at $z < 0.5$, as detailed in Table III. More details can be found in AQG. We consider both spectroscopic surveys ($\delta z = 0$) and photometric surveys ($\delta z/z = 0.04$) and three areas (1000, 5000, 10000 deg^2). These features are well within the range of proposed experiments like JDEM and DUNE (Crotts at al. 2005; Réfrégier et al. 2006; see also DETF Report Albrecht et al. 2006)

We first consider Case I, in which the growth factor is not an independent quantity but is a function of $w(z)$. The two-dimensional regions of confidence are shown in Fig (2) and the final marginalized errors are summarized in Tab. (IV). The errors on w_p reduce from 0.036 to 0.012 for the spectroscopic case for surveys that extend from 1000 to 10000 deg^2 and from 0.054 to 0.018 in the photometric case.

Then we consider Case II, in which γ is a free constant as in eq. (1). In Fig. (4) we show the confidence regions

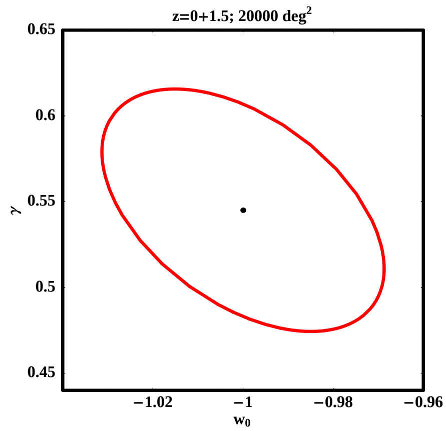

Figure 6: Confidence level for w_0 and γ for surveys 20000 deg^2 (DETF case). The solid red curve refers to spectroscopic surveys.

for $w_0 - \gamma$. The errors are given in Tab. (V) . We see that the errors on γ reduce from 0.099 to 0.05 for spectroscopic surveys and from 0.301 to 0.114 in the photo-z case. These errors are way too large to produce an independent constraint on w (in fact one has approximately $\Delta w \approx 10\Delta\gamma$ near $w = -1$) but, beside being a general test of consistency for the cosmological model, they would certainly give interesting constraints on models that predict growths different from standard, like modified gravity models (Koyama & Maartens 2005; Maartens 2006; Amendola, Charmousis & Davis 2005; Amendola, Polarski, Tsujikawa 2006). In Fig. (3) we show the FOM for $w_p - w_1$, for only one survey ($5000\,deg^2$) and only one combination of redshift ($z = 1 - 3$), first when all the other parameters are fixed and then successively marginalizing over the parameter indicated and over all those on the left (eg the third column represents the marginalization over ω_m, ω_b).

We can compare our results to those obtained recently by Huterer and Linder (2006). Using a combination of weak lensing, SNIa and CMB methods, they predict $\sigma(\gamma) = 0.044$ for future experiments. With large-scale tomographic weak lensing alone, Amendola, Kunz, and Sapone (2007) predict $\sigma(\gamma) = 0.04$ at 68% confidence level. These values are comparable to those obtained here with the BAO method and considering a spectroscopic survey of $5000 deg^2$, $\sigma(\gamma) = 0.059$.

We notice that the difference on the growth index γ between General Relativity and an extradimensional gravity model (as DGP, where $\gamma = 0.68$, see Linder & Cahn 2007) is $\Delta\gamma = 0.135$; if we compare our results shown in Tab. (V) we see that the errors on γ for a photometric survey are within this range, meaning that DGP model cannot be escluded. Things get slightly better if we consider spectroscopic surveys, where errors decrease with about 30%; however in this case we require a large survey extended from $z = 1$ to $z = 3$ with an area of $10000\,deg^2$ to distinguish with sufficient confidence DGP

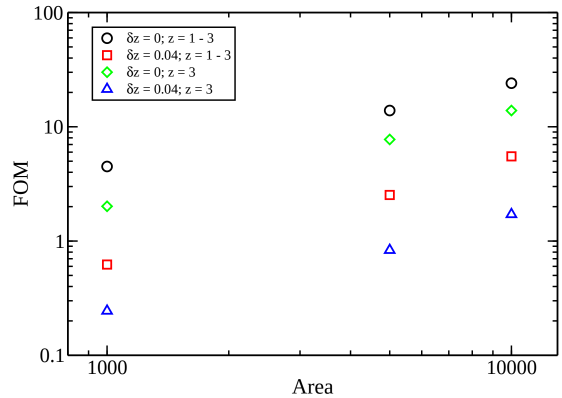

Figure 7: Effect of Survey geometry on the dark energy FOM. We plotter the FOM $(w_p - w_1)$ for spectroscopic surveys ($\delta z = 0$) and photometric surveys ($\delta z = 0.04$) as a function of the area.

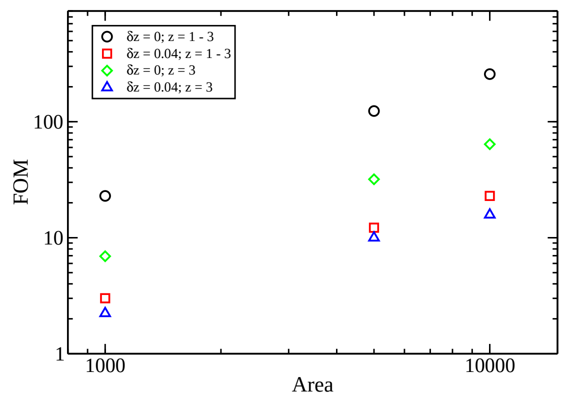

Figure 8: Effect of Survey geometry on the dark energy FOM. We plotter the FOM $(w_0 - \gamma)$ for spectroscopic surveys ($\delta z = 0$) and photometric surveys ($\delta z = 0.04$) as a function of the area.

from ΛCDM. In Fig. (6) is shown the confidence region for $w_0 - \gamma$ for a survey extended from $z = 0$ to $z = 1.5$ and an area of $20000\,deg^2$ (DETF case): the error on γ reduces to $\sigma(\gamma) = 0.06$.

In Fig. (7) we also show the figure-of-merit (FOM) suggested by the Dark Energy Task Force report (Albrecht et al. 2006) as a simple measure of the constraining power of an experiment. The FOM is defined as the inverse of the area that encloses the 95% confidence region and can be found simply as $(6.17\pi\sqrt{\det F})^{-1}$. In Fig. (8) we plot the FOM for w_0 and γ. The general trend is that the FOM for spectroscopic surveys are roughly 4-6 times higher than for similar 4% error photo-z surveys. It will be interesting to compare our FOM on the plane w_0, γ with those obtained from other experiments. This task will be performed in future work.

Acknowledgments

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